A novel fiber optic sensor to monitor beef meat emulsion stability using visible light scattering

D. Álvarez [a,b,*], M. Castillo [a], F.A. Payne [a], Y.L. Xiong [b]

[a] Department of Biosystems and Agricultural Engineering, University of Kentucky, 128 C.E. Barnhart Building, Lexington, KY 40546-0276, USA
[b] Department of Animal and Food Sciences, University of Kentucky, 206 W.P. Garrigus Building, KY 40546-0275, USA

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ABSTRACT

Accurate control of the meat emulsification process for a consistent product quality entails the development of an on-line optical sensor technology to determine the optimum chopping end-point yielding minimum cooking loss and a fine texture. Previous studies suggested that light backscatter measurements can be used to monitor physical–chemical changes during emulsification in comminuted meat products if appropriate spacing between the emitting and detecting optical fibers is used. Light backscatter intensity from beef emulsions manufactured with different fat/lean ratio (0.075, 0.250, and 0.330) and chopping duration (2, 5, and 8 min) were obtained using a dedicated fiber optic prototype. Optical measurements were collected at three radial distances (2, 2.5, and 3 mm) from the light source using a fiber optic spectrometer (300–1100 nm). Light backscatter intensity decreased logarithmically with increasing fiber optic spacing. Light propagation through the emulsion decreased significantly with increasing chopping duration and fat concentration. Cooking loss increased with increasing fat/lean ratio and with under- or over-chopping. The maximum emulsion stability was observed at 5 min of chopping. Several optically derived parameters were found to be significantly correlated with fat loss during cooking. Typically, those correlations were observed to increase with decreasing fiber distance. Based on these findings, an optical configuration is proposed that would compensate for the emulsion heterogeneity, maximizing the existing correlation between the optical signal and the emulsion quality metrics.

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1. Introduction

Finely comminuted meat products are an integral part of diet in developed nations like the US (USDA, 2005) and have great economic importance. Frankfurters and bolognas are the most popular comminuted products in the US and account for the 25% of all sausages sold (NHDSC, 2006). In 2007, consumers spent more than $4.1 billion on hot dogs and sausages in US supermarkets – that equals more than 1.5 billion pounds of hot dogs and sausages bought at retail stores alone. Experts believe sales of processed meat will continue to grow in the future. Estimates place total dollar sales at more than $22 billion by 2009. Base on an average cooking loss (weight, %) of 2.64 (optimum chopping conditions), the estimated economic loss resulting from non-optimum emulsion stability during the cooking process was estimated to range between 0.2 and 1.65 billion dollar per year. Improving process control and automation of the meat emulsification process will reduce the economical impact of emulsion breakdown in meat industry worldwide. Currently, there is a lack of an effective on-line technology to select the optimum length of the chopping process during meat emulsification that results in maximum emulsion stability during the heat treatment. Control improvement will require the development of suitable sensor technologies to monitor the optimum level of emulsification that would maximize yield, quality and consistency of the finely comminuted meat products.

Various methods have been suggested over the years to short and classify meat that could assist on preventing cooking losses induced by inappropriate meat emulsification. Color sensors to sort out pale, soft and exudative (PSE) pork meats (Bendall & Swatland, 1988) as well as dark, firm and dry (DFD) meats (McDougall & Jones, 1981) have been used especially in pork and beef carcasses. Carcass Fat-Depth Probes such as "Hennessy Probe" and "Fat-o-Meater" are currently used by the meat industry to grade pork carcasses by inserting them thought the backfat (Swatland, 1995). Infrared (IR) sensors are currently used worldwide to determine the chemical composition of food products, including raw beef/pork meat emulsions (Ben-Gera & Norris, 1968; Lanza, 1983), as well as their sensory quality (Ellekjaer, Isaksson, & Solheim, 1994). Connective tissue fiber optic sensor technology has been designed to measure collagen florescence and estimate the tenderness of meat cuts (Swatland, 1991).

Several authors (Serdaroglu, 2006; Álvarez, Castillo, et al., 2007) have observed the correlation between emulsion color parameters and fat and water losses induced by the emulsion heat treatment so that cooking losses can be predicted from the change on the raw emulsion lightness (L^*) during the chopping process. These evidences suggest that light backscatter intensity could also be correlated with physical–chemical properties changing during emulsification and impacting emulsion stability. On the other hand, there are some precedents of using light backscatter for on-line monitoring of key food manufacturing processes. For instance, a light backscatter fiber optic sensor has been used to predict milk gelation time (Castillo, Lucey, & Payne, 2004) and curd cutting time (Payne, 1995) during cheese manufacture. Castillo, Payne, and Shea (2005) were developed a promising light scatter sensor technology that was able to monitor milk coagulation and curd syneresis on-line. This optical technology was recently used by Fagan et al. (2007) to predict curd moisture content during syneresis over a moisture range of 50%–90% as well as whey fat losses and cheese yield.

The use of a real-time meat emulsion stability sensor technology having the ability to determine the optimum chopping endpoint would significantly improve the current control over the chopping process preventing both under and over-chopping defects, which would result in evident final product yield, consistency and quality gain.

The goal of this work was the study of the optical properties of beef emulsions having different fat/lean ratio at various chopping durations and at several distances between the emitting and detecting optical fibers in order to detect changes in comminuted meats that may be correlated with those technological parameters associated with emulsion stability (e.g., cooking losses, water, and fat separation, etc.). The study of these optical properties is essential for the development of an on-line light backscatter fiber optic sensor to monitor stability during the meat emulsification process.

2. Materials and methods

2.1. Experimental design

Light backscatter properties of beef meat emulsions were evaluated for the development of an optical sensor technology to determine emulsion stability. A randomized block design (Fig. 1) was carried out to evaluate the effect of two different treatment factors, distance (D) between the emitting and detecting optical fi-

Table 1
Least square means (LSM) of the target and current fat/lean ratio (R_{FL}) values for the three meat batches utilized in this experiment[a]

	Block	CT (min)	Target R_{FL}		
			0.075	0.250	0.330
Current R_{FL}	1	2	0.075[a]	0.241[a]	0.369[a]
	2	5	0.070[a]	0.281[a]	0.366[a]
	3	8	0.076[a]	0.263[a]	0.388[a]

[a] LSM with same letters were not significantly different ($P < 0.05$).

bers and fat/lean ratio (R_{FL}), on the light backscatter intensity spectral scan of the emulsions at different chopping times (CT; blocking factor). Experiments within each CT block (2, 5, and 8 min) were replicated three times. At each CT, the effect of different levels of fat/lean ratio (0.075, 0.250, and 0.330) on visible (450 and 700 nm) light backscatter intensity collected at three different radial distances (2, 2.5, and 3 mm) from the emitting light source were evaluated (Fig. 1), as well as those technological parameters associated with emulsion stability (i.e., water and fat separation).

A different batch of meat was assigned to each experimental block. Since block and batch effects were not independent, the three different meat batches were sampled and analyzed for chemical composition to disregard a potential confounding effect between meat batch and the experimental blocks. Table 1 shows the target and the current fat/lean ratios for the three meat batches utilized in this experiment. No significant differences ($P < 0.05$) were found between blocks for the least square means of R_{FL} at any of the three target R_{FL} experimental levels, which discard a batch-block confounding effect.

2.2. Sample preparation and meat emulsion manufacturing

Commercial fresh ground beef samples were obtained from a local meat purveyor (Kroger Co. Cincinnati, OH). Color, pH and chemical composition (fat and moisture) of each meat batch were measured before processing. The raw materials, with the specific R_{FL}, were weighted and vacuum packed into individual plastic bags and frozen at $-18\,°C$ until use. Before emulsion manufacturing, frozen samples were thawed to $\sim 1\,°C$, and further cut into small pieces in order to facilitate the mixing of ground meat with the additives before chopping. Each emulsion was prepared using 100 g of ground beef, 6.35 g of additives (hot dog seasoning RD 105-68A, United Food Ingredients, Inc., Beecher, Illinois, USA) and

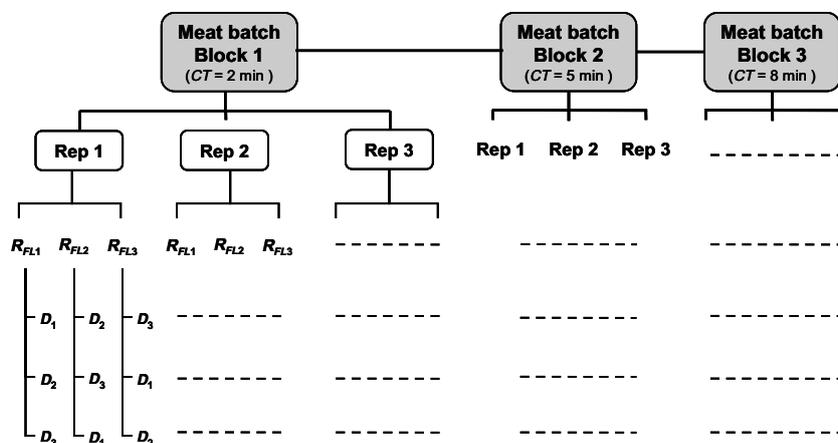**Fig. 1.** Experimental design utilized to evaluate the optical properties of beef emulsions. Three chopping durations (CT = 2, 5, and 8 min), three fat/lean ratios (R_{FL1}, 0.075; R_{FL2}, 0.25; and R_{FL3}, 0.33) and three distances between optical fibers (D_1, 2 mm; D_2, 2.5 mm; and D_3, 3 mm) were studied. Measurements were assigned to treatments in a random order within blocks and replications.

26 g of ice. Ground beef samples and ingredients were comminuted in a bowl chopper (KitchenAid, Mod. KFP710, St. Joseph, Michigan, USA) at 1,750 rpm for 2, 5, and 8 min (blocks 1, 2, and 3, respectively). Immediately after chopping, temperature and pH of the meat emulsions were measured using a Traceable® Thermometer (Mod. 15-078G, Control Company, TX, USA) and an Oakton® pHtester (Mod. Spear, Eutech Instruments, Malaysia), respectively. The pHtester was calibrated before measurements with buffers 4.01 and 7.00 perPHect® solutions (Thermo Electron Corporation, Baverly, MA, USA). Color and chemical composition of the emulsions were also measured as described is Sections 2.3 and 2.4, respectively.

2.3. Color measurement of raw emulsions

The color of each sample was measured 1 h after the emulsion was prepared using a Spectrocolorimeter Minolta Chromameter II (Mod CR-310, Minolta Camera Co., Osaka, Japan) having a CIE standard 'C' illuminant and 0° viewing angle geometry. A pulsed xenon arc (PXA) lamp inside a mixing chamber provided diffuse, even lighting over a 50 mm diameter measuring area. Only the light reflected perpendicular to the sample surface was collected by the optical-fiber cable for color analysis. The measurements were performed in a 10.5 cm diameter plate (Glass Light-Projection Tube, CR-A33e). The chromameter was calibrated before color measurements were taken using a calibration plate CR-A44 ($Y = 93.80$, $x = 0.3138$, $y = 0.3195$). The CIELAB color space was selected in this study to measure the L^* value (metric lightness) and chromaticity coordinates a^* (redness/greenness) and b^* (yellowness/blueness). Measurements were repeated six times in different areas of the surface of each emulsion and the average color was recorded.

2.4. Proximate analysis of ground beef samples and raw meat emulsions

Chemical composition (fat and moisture, %) of the commercial fresh ground beef samples and raw meat emulsions were analyzed using a HFT-2000 fat analyzer (DSC – Data Support Co. Inc., Encino, CA, USA; accuracy of ±0.5%). The fat analyzer was previously calibrated and programmed to determine fat and moisture concentration in beef meat. Samples of ~3 g were weighted in a balance Adventure™ (Mod. ARA520, Ohaus® Corp., USA) over a glass fiber pad (Mod. 1019, Data Support Co. Inc., USA). Then, samples were covered with another pad, gently pressed, and placed into the fat analyzer plate for measurement. Samples were measured in duplicate and the average was recorded.

2.5. Cooking loss measurements

Once the chopping process was completed, cooking loss (C_L) of each emulsion sample was measured in triplicate. Three 30 g aliquots of each meat emulsion were stuffed into plastic screw tap test tubes. The aliquots were heat treated in a scalding bath (Lauda RM20. Brinkman Instruments Inc., NY, USA) at 70 °C for 30 min and then quickly refrigerated in a cool water bath (Lauda Ecoline RE220. Brinkman Instruments Inc.) for 10 min at 5 °C. Total C_L (%) of the samples was calculated from the weight of the final cooked emulsion (W_F) and the initial weight (W_0) of the sample before cooking as follows:

$$C_L = \frac{W_0 - W_F}{W_0} 100. \tag{1}$$

Cooking fat losses C_{LF} (%) of the samples were estimated from the difference between W_F and the liquid exudates (W_E) drained from the container after emulsion heat treatment as follows:

$$C_{LF} = \frac{W_F - W_E}{W_0} 100. \tag{2}$$

Note that fat content on the liquid exudates was assumed to be negligible for C_{LF} estimation as most fat exudates were observed to be retained on the plastic screw tap test tube.

2.6. Light backscatter measurement of raw emulsions

A dedicated laboratory optical sensor prototype was designed, built and tested in the Food Engineering Lab (University of Kentucky) to measure light backscatter of comminuted meats at different distances (Fig. 2) with the aim of identifying and detecting physical–chemical changes occurring during chopping that may be correlated to emulsion stability. This optical sensor prototype was designed to set the radial distance between the emitting and detecting optical fibers by means of a micrometer. As observed in Fig. 2, two small plastic probes were built and configured such that light backscatter from the sample could be detected using a High-Resolution Fiber Optic Spectrometer (Model HR4000, Ocean Optics, Inc., Dunedin, FL, USA). The light source utilized was a tungsten halogen (300–1100 nm) bulb (LS-1, Ocean Optics, Inc.). Fiber optic cables were manufactured using 600 μm diameter fibers (Spectran Specialty Optics, Avon, CN, USA). The terminating (i.e., measuring) ends of the two fibers were built into the plastic probes while the other two ends were connected, using an SMA connector, to the spectrometer and light source, respectively, as shown in Fig. 2. The data acquisition system consisted of a PC connected by a USB port to the spectrometer and programmed for data acquisition with SprectraSuit Spectroscopy platform software (Ocean Optics, Inc.). Before each measurement, the terminating ends of the fibers were aligned vertically and horizontally to the same level. Emulsion samples were placed in a double-jacketed sample holder. The fiber tips were immersed into the emulsion sample up to a final depth of ~12.7 mm from the surface of the sample. The temperature of the sample was controlled by means of connecting the sample holder to a water bath (Lauda Ecoline RE220. Brinkman Instruments Inc. NY. USA; ±0.01 °C of accuracy). The temperature of the emulsion was monitored using a Traceable® Thermometer inserted into the emulsion. An opaque enclosure was used to isolate the sample from ambient light interference. Light backscatter intensity of the samples was measured at the target radial distances according to the experiment design described in Section 2.1, and at an integration time (IT) ranging from 19 to 60 s where IT was the detector light exposure time. The light scattering spectral scans, $I(\lambda)$, were automatically processed by subtracting the respective dark spectral scans and dividing by the IT to give the light scattering normalized spectral scans, $I_N(\lambda)$ (bits s^{-1}). A number of optical parameters defined in Table 2 were obtained from the normalized spectral scans. Fig. 3 shows a typical beef emulsion normalized spectral scan as well as the corresponding optical parameters obtained.

2.7. Statistical analysis

Data were analyzed using the Statistical Analysis System (SAS®, 2002). Pearson correlation coefficients, r, were determined by the correlation (CORR) procedure of SAS. The analysis of variance (ANOVA) was performed using the general linear model (GLM) procedure of SAS. The least squares means (LSM) and significance of treatments were calculated using type IV sum of squares. LSM were considered to be statistically different when $P < 0.05$.

3. Results and discussion

Meat emulsification of fresh beef meat samples was monitored by optical methods. Simultaneous measurement of color and sev-
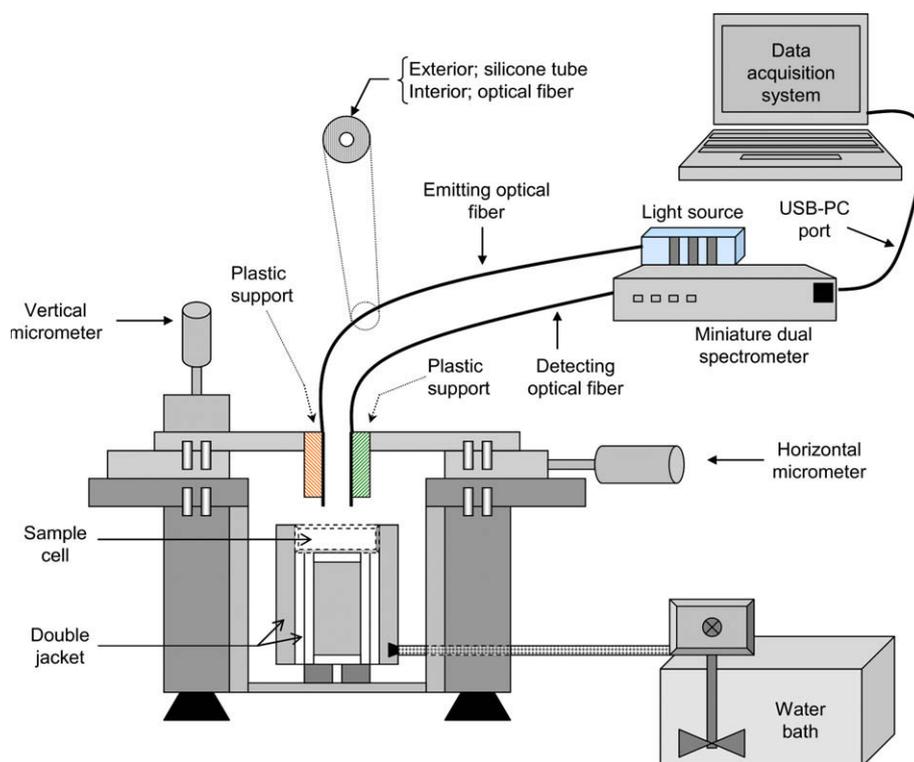
Fig. 2. Optical device and measurement set up used to measure light backscatter in meat emulsions at different radial distances from the light source.

Table 2
Definition of optical parameters derived from the normalized light backscatter intensity spectral scan[a]

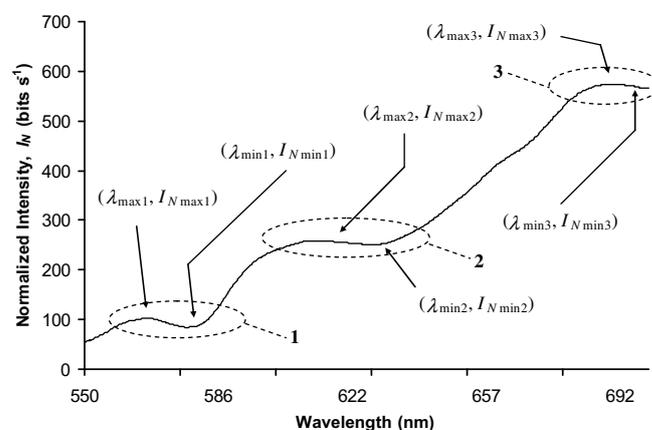| Spectral scan					
Local maxima			Local minima		
Peak position	I_N	λ	Peak position	I_N	λ
1st ($\sim$565 nm)	I_{Nmax1}	λ_{max1}	1st ($\sim$577 nm)	I_{Nmin1}	λ_{min1}
2nd ($\sim$620 nm)	I_{Nmax2}	λ_{max2}	2nd ($\sim$628 nm)	I_{Nmin2}	λ_{min2}
3rd ($\sim$690 nm)	I_{Nmax3}	λ_{max3}	3rd ($\sim$693 nm)	I_{Nmin3}	λ_{min3}

[a] I_N, Normalized light backscatter intensity.

Fig. 3. Normalized light backscatter spectral scan. Data corresponded to beef meat emulsions made using 2 min of chopping and a fat/lean ratio of 0.075. Measurement was made at 2 mm from the emitting light source. Spectrum was divided into three areas, green–yellow (1), orange–red (2), and red (3) intensity regions as described in Section 3.3.

eral emulsion quality metrics (pH, temperature, fat, moisture and cooking loss) was performed on fresh and cooked emulsions. An ANOVA was conducted to determine the main sources of variation in the optical parameters (Model I). Replicate (R) and experimental factors R_{FL}, CT, and D were selected as main effects in the preliminary ANOVA model. The main interactions $CT \times R_{FL}$, $CT \times D$, and $R_{FL} \times D$ were also included. Replication effect was not significant and was removed from the model. Since non-optical parameters studied were independent of the radial distance, a second ANOVA, identical to Model I but excluding D as main effect, was required (Model II). As in Model I, replication effect was not significant for Model II and hence it was removed from the Model. Table 3 shows the ANOVA (Models I and II) for the dependent variables studied, which were highly significant in all the cases. In Model I, CT and D were significant sources of variation for all the dependent variables studied except for λ_{max2} and I_{Nmin1}, respectively. R_{FL} was significant for the optical parameters IT, Pk, λ_{max2}, λ_{min1}, I_{Nmax1}, I_{Nmax2}, and I_{Nmin2}. The interaction terms $CT \times R_{FL}$ and $CT \times D$ were highly significant ($P < 0.001$) for IT, Pk, I_{Nmax2}, I_{Nmax3}, I_{Nmin2}, I_{Nmin3}, and λ_{min1}. For Model II, the main effects CT and R_{FL}, as well their interaction term, were highly significant for all dependent variables studied with few exceptions. R_{FL} was not significant for T while the interaction term $CT \times R_{FL}$ was not significant for pH, T and C_{LF}.

3.1. Physical–chemical changes during the emulsification process

3.1.1. Relationship between light backscatter response and emulsion quality metrics

Table 4 shows the effect of R_{FL}, CT, and D on the least square means (LSM) of light backscatter parameters, color coordinates and emulsion quality metrics. It was found that T increased significantly ($P < 0.001$) from $\sim$7 to 19 °C as a result of the chopping process. The pH also increased significantly ($P < 0.001$) from $\sim$5.6 to 5.9 during the first 5 min of chopping. However, at longer chopping time a slight but significant pH decrease was observed (Table 4). A significant ($P < 0.001$) correlation was found between C_L and pH ($r = -0.41$). This might evidence that the chopping operation exerts

Table 3
Analysis of variance and F statistics for dependent variables studied[a],[b]

Model			Variation source				
			R_{FL} (DF = 2)	CT (DF = 2)	D (DF = 2)	$CT \times R_{FL}$ (DF = 4)	$CT \times D$ (DF = 4)
I	R^2	F	F	F	F	F	F
IT	0.97	122***	11.7***	432***	623***	8.84***	5.41***
Pk	0.97	122***	11.7***	432***	623***	8.84***	5.41***
λ_{max1}	0.66	6.78***	ns	34.0***	14.1***	2.74*	3.07*
λ_{max2}	0.92	38.4***	3.80*	ns	334***	ns	ns
λ_{max3}	0.81	14.1***	ns	17.0***	99.0***	ns	ns
I_{Nmax1}	0.91	32.5***	3.84*	68.0***	213***	ns	3.47*
I_{Nmax2}	0.95	71.4***	6.15**	215***	287***	14.5***	51.2***
I_{Nmax3}	0.96	87.4***	ns	197***	477***	12.4***	36.1***
λ_{min1}	0.98	153***	8.86***	571***	669***	10.3***	41.7***
λ_{min2}	0.43	2.64**	ns	4.70*	5.61**	3.05*	ns
λ_{min3}	0.49	3.20***	ns	6.47**	9.30***	2.68*	ns
I_{Nmin1}	0.74	7.17***	ns	36.0***	ns	ns	ns
I_{Nmin2}	0.94	56.4***	5.25**	172***	209***	13.6***	45.5***
I_{Nmin3}	0.96	85.8***	ns	188***	476***	12.0***	35.0***
II			R_{FL} (DF = 2)	CT (DF = 2)		$CT \times R_{FL}$ (DF = 4)	
pH	0.94	36.7***	7.98***	138**	–	ns	–
T	0.81	9.66***	ns	34.3***	–	ns	–
L^*	0.93	30.7***	47.4***	68.2***	–	3.50*	–
a^*	0.94	35.8***	22.0***	106***	–	7.32**	–
b^*	0.95	46.9***	78.0***	99.1***	–	5.27**	–
CL	0.87	15.0***	42.7***	10.3**	–	3.54*	–
C_{LF}	0.83	10.9***	24.9***	13.5***	–	ns	–

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
[a] $N = 81$ and 27 for Models I and II, respectively. R^2, determination coefficient; F, ANOVA F-statistic; DF, degree of freedom; the interaction $R_{FL} \times D$ (DF = 4) was not significant and was removed from the table.
ns not significant.
[b] R_{FL}, fat-lean ratio; CT, chopping time; D, distance between emitting and detecting optical fibres; $CT \times R_{FL}$, chopping time × fat-lean ratio; $CT \times D$, chopping time × distance; $R_{FL} \times D$; fat-lean ratio × distance; for definition of dependent variables, see "Materials and Methods" (Section 2.6), and Table 2.

an indirect effect on meat emulsion stability, and consequently over C_L, by inducing chemical changes in the emulsion matrix (e.g. an increase of T or a decrease of pH would decrease emulsion stability and, in turn, increase C_L). Pearson correlations between dependent variables studied are presented in Table 5. As it can be observed, light backscatter response seemed also to be affected by the physical–chemical changes occurring during chopping. This was evidenced by the significant increase ($P < 0.001$) of both IT and total number of local maxima/minima identified on the spectral scans (Pk) with increasing T and pH. The decrease ($P < 0.01$) of light scatter intensity observed as T and pH increased pointed also on this direction. These results agreed with those obtained by Ockerman and Wu (1990), who observed that C_L was significantly and positively correlated with emulsion temperature. It is well-kwon that if the emulsion temperature is higher than 15–20 °C the emulsion viscosity decreases and, consequently, velocity of fat separation increases, leading to emulsion breakdown (Ordóñez et al., 1998). Increasing emulsion temperature over 50 °C also enhances denaturation of myofibrilar proteins (Barbut, Gordon, & Smith, 1996) and coalescence of fat globules, all of which decreases the emulsifying capacity of proteins. In agreement with Serdaroglu (2006), no clear relationship was found between R_{FL} and either pH or T. However, a direct effect of R_{FL} on C_L and C_{LF} was observed (Table 4). C_L increased from ∼18% to 29% as R_{FL} increased from 0.075 to 0.33. Moreover, C_{LF} presented the highest correlation with the optical parameters derived from light backscatter intensities (i.e. I_{Nmax3}; $r = -0.41$; $P < 0.001$), while C_L only showed a slight correlation with wavelength-based optical parameters (i.e. λ_{min1}; $r = -0.26$; $P < 0.05$) (Table 5). A significant ($P < 0.001$) and positive correlation was found between C_{LF} and the optical parameters IT and Pk while the light backscatter intensity at all the local maxima and minima suffered a significant ($P < 0.05$) decreased with increasing C_{LF}. These results suggest that the light backscatter intensity spectral scan contains important information about emulsion stability during the cooking process. In agreement with our results, Chen and Marks (1998) observed that visible/NIR ($\lambda = 400$ to 2500 nm) spectroscopy appeared to have the best potential to evaluating cooking loss. They concluded that visible/NIR spectroscopy might be used for rapid monitoring of physical characteristics during meat thermal processing. Other authors have also provided experimental evidences supporting that fat and water losses during cooking of meat emulsions can be predicted from the change on the emulsion lightness (L^*) during the chopping process (Barbut, 1998; Álvarez, Castillo, et al., 2007). According to these results, the development of a light backscatter optical technology to minimize fat and water separation during cooking might be feasible.

3.1.2. Relationship between emulsion color and light backscatter response

As it can be observed in Table 5, a significant ($P < 0.05$) decrease of light backscatter intensity was found at all the spectral scan local maxima/minima as lightness increased. Optical parameters, IT and Pk were positively and significantly ($P < 0.001$) correlated with color parameters L^*, a^*, and b^*. L^* also had a negative correlation with the wavelength measurement, λ_{min3} ($r = -0.55$; $P < 0.001$). Similarly, color coordinates a^* and b^* were highly correlated with several light backscatter intensity parameters such as I_{Nmax1}, I_{Nmax3}, and I_{Nmin1} ($P < 0.001$). The correlation between these color coordinates and the wavelengths λ_{max2}, λ_{max3}, λ_{min1}, λ_{min2}, and λ_{min3} was also significant ($P < 0.05$). Previous experimental evidences by Barbut (1998) and Álvarez, Castillo, et al. (2007) supported that fat and water losses during the meat emulsion heat treatment can be predicted from the change on the emulsion lightness (L^*) during

Table 4
Influence of main effects (fat/lean ratio, chopping time and distance) on light backscatter parameters, color and meat emulsion quality metrics.

	R_{FL}			CT (min)			D (mm)		
	0.075	0.25	0.33	2	5	8	2.0	2.5	3.0
IT (s)	35.7[a]	35.6[a]	37.8[b]	30.1[a]	34.0[b]	45.0[c]	27.0[a]	36.5[b]	45.6[c]
Pk	7.40[a]	7.40[a]	7.60[a]	5.40[a]	8.30[b]	8.70[b]	6.50[a]	7.10[a]	8.80[b]
λ_{max1}	560[a,b]	561[a]	560[b]	561[a]	560[a]	560[a]	557[a]	558[a]	566[b]
λ_{max2}	616[a]	617[a,b]	618[b]	615[a]	617[b]	619[b]	614[a]	615[a]	622[b]
λ_{max3}	685[a]	686[b]	685[a,b]	688[a]	684[b]	683[b]	682[a]	683[b]	691[c]
I_{Nmax1}	24.6[a]	25.7[a]	20.4[b]	42.3[a]	18.1[b]	10.4[c]	45.3[a]	16.7[b]	8.80[c]
I_{Nmax2}	131[a,b]	133[a]	121[b]	187[a]	119[b]	80.0[c]	222[a]	105[b]	58.6[c]
I_{Nmax3}	268[a]	275[a]	248[b]	386[a]	234[b]	170[c]	393[a]	239[b]	158[c]
λ_{min1}	577[a]	577[ab]	576[b]	578[a]	577[a]	576[b]	578[a]	576[b]	576[b]
λ_{min2}	627[a]	628[a]	627[a]	627[a]	628[b]	627[a]	628[a]	628[a]	626[b]
λ_{min3}	ø	ø	ø	ø	693[a]	691[b]	ø	694[a]	694[a]
I_{Nmin1}	21.0[a]	22.7[a]	17.3[b]	38.4[a]	14.2[b]	8.40[c]	40.0[a]	14.8[b]	6.10[c]
I_{Nmin2}	132[a,b]	134[a]	123[b]	188[a]	120[b]	81.8[c]	224[a]	107[b]	58.0[c]
I_{Nmin3}	ø	ø	ø	ø	242[a]	177[b]	ø	253[a]	155[b]
L^*	48.0[a]	52.5[b]	56.7[c]	46.8[a]	53.1[b]	57.2[c]	–	–	–
a^*	16.2[a]	15.4[b]	13.8[c]	12.2[a]	17.4[b]	15.8[c]	–	–	–
b^*	20.6[a]	23.0[b]	24.8[c]	20.1[a]	23.9[b]	24.4[c]	–	–	–
C_L (%)	17.6[a]	21.9[b]	29.0[c]	24.0[a]	19.6[b]	24.9[a]	–	–	–
C_{LF} (%)	3.50[a]	3.40[a]	7.00[b]	3.20[a]	4.50[b]	6.20[c]	–	–	–
pH	5.80[a]	5.70[b]	5.70[b]	5.63[a]	5.92[b]	5.80[c]	–	–	–
T (°C)	12.3[a]	13.0[a,b]	14.0[b]	7.21[a]	12.8[b]	19.3[c]	–	–	–

R_{FL}, fat/lean ratio; CT, chopping time; D, distance between emitting and detecting optical fibres. For definition of dependent variables, see "Materials and Methods" (Section 2.6), and Table 2. ø, not measured because no local minimum was detected.
[a–c] LSM with same letters were not significantly different (P < 0.05); number of replications = 3; N = 81 and 27 for Models I and II, respectively.

Table 5
Pearson correlation between light backscatter parameters, color coordinates and meat emulsion quality metrics[a]

	pH	T	C_L	C_{LF}	L^*	a^*	b^*
IT	ns	0.52***	0.23*	0.43***	0.49***	ns	0.38***
Pk	0.49***	0.39***	ns	0.36***	0.44***	0.42***	0.43***
λ_{max1}	ns	ns	ns	ns	ns	ns	ns
λ_{max2}	ns	0.28*	ns	0.25*	0.32**	ns	0.30**
λ_{max3}	−0.36**	−0.30**	ns	ns	−0.28*	−0.35**	−0.30**
I_{Nmax1}	−0.42***	−0.48***	ns	−0.33**	−0.44***	−0.40***	−0.40***
I_{Nmax2}	−0.32**	−0.44***	ns	−0.34**	−0.43***	−0.26*	−0.35**
I_{Nmax3}	−0.47***	−0.53***	ns	−0.41***	−0.51***	−0.42***	−0.47***
λ_{min1}	ns	−0.25*	−0.26*	−0.34**	−0.35**	ns	−0.28*
λ_{min2}	0.29**	ns	ns	ns	ns	0.35**	ns
λ_{min3}	−0.42***	−0.57***	ns	−0.39**	−0.55***	−0.35**	−0.55***
I_{Nmin1}	−0.44***	−0.48***	ns	−0.32**	−0.42***	−0.42***	−0.40***
I_{Nmin2}	−0.32**	−0.43***	ns	−0.33**	−0.42***	−0.25*	−0.35**
I_{Nmin3}	ns	−0.28*	ns	−0.28*	−0.27*	ns	ns
L^*	0.32**	0.78***	0.59***	0.84***	–	–	–
a^*	0.86***	0.35**	−0.59***	ns	–	–	–
b^*	0.43***	0.69***	0.45***	0.73***	–	–	–

* P < 0.05.
** P < 0.01.
*** P < 0.001.
ns not significant.
[a] N = 81 (Model I) and 27 (Model II). For the definition of dependent variables, see "Materials and Methods" (Section 2.6), and Table 2.

the chopping process. Thus, the high correlations observed between optical and color parameters, especially with L^* values, suggest that light backscatter could have potential as indicator of emulsion stability during finely comminuted meat product manufacturing. This finding shows the feasibility of an optical sensor technology to predict the optimum chopping end-point.

3.2. The effect of chopping time on color and meat emulsion quality metrics

The effect of CT on the LSM values of color coordinates reported in Table 4 shows that color parameters L^* and b^* significantly (P < 0.001) increased as CT increased while color coordinate a^* was

at a maximum at $CT = 5$ min, decreasing towards the end of the chopping process. The trends observed on fresh emulsions color coordinates as a result of CT can be explained in terms of emulsion stability. It was hypothesized that CT would induce emulsion satiability changes that would impact both raw emulsion color and fat proportion of the exudates generated during cooking. This hypothesis was evaluated by the ratio of fat exudation (R_{FE}) defined as C_{LF}/C_L. It was found that R_{FE} was positively and strongly correlated ($r = 0.99$) with both L^* and b^*. These correlations suggest that the degree of fat stabilization on fresh emulsions might be responsible not only for the lightness and yellowness of the fresh emulsions, but also for changes on the ratio of exudation, R_{FE}, with different CT. Redness, a^*, of the emulsions was expected to be related to the concentration

of myoglobin (Ayo, Carballo, Solas, & Jiménez-Colmenero, 2007). Assuming that 21.40% of the beef lean is protein and 0.36% of the protein is myoglobin (Tscheuschner, 2001), it was estimated that the 0.075, 0.25, and 0.33 R_{FL} meat emulsions contained 0.72, 0.62, and 0.58 g of myoglobin per 100 g of emulsion. As expected, it was observed that myoglobin concentration was strongly and negatively correlated to a^* (r = −0.84). Red color in meat is also influenced by the equilibrium oxymyoglobin/metmyoglobin (Boles, Mikkelsen, & Swan, 1998) according to the following chemical reaction (Cheftel & Cheftel, 1992):

$$Mb^{2+} + H^+ + 1/4 O_2 \rightarrow Met Mb^{3+} + 1/2 H_2O. \tag{3}$$
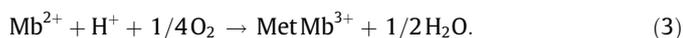
Consistently, higher b^* values were observed at $CT = 5$ when pH reached its maximum value (Table 4). Note that the concentration of protons decreases with increasing pH and them the reaction (Eq. (3)) has a tendency to proceed in the reverse direction, towards reactants, which increases both myoglobin concentration (i.e., redness) and the emulsion water holding capacity (i.e., reduced exudation). A relationship between the rate of myoblogin formation, redness and water holding capacity has been previously established by Boles et al. (1998).

Regarding the effect of CT on cooking losses, Table 4 shows that largest cooking exudations were detected in the emulsions with larger or shorter CT ($C_L > 24\%$). Fat losses showed a steady increased by ~50% as CT increased from 2 to 8 min. The largest fat exudation ($C_{LF} > 6\%$) was observed at $CT = 8$ min. Under-chopping results in minimal binding because fat particles are too large to yield a stable product (Lee, 1985). Over-chopping results in massive fat and water separation during cooking because fat particles are very small and their total surface rapidly increases. This yields an unstable product because more protein is required to emulsify the fat (Hedrick, Aberle, Forrest, Judge, & Merkel, 1994). Similar behavior was also observed by Brown and Toledo (1975), Barbut (1998) and Álvarez, Castillo, et al. (2007).

As suggested above, pH changes induced as a result of the chopping process also seems to play a role on the C_L extent. The emulsion pH was at a maximum (5.92) at $CT = 5$ min. At this time, not only b^* values were at a maximum, but also C_L was at a minimum ($C_L = 19.6\%$; e.g., optimum emulsion stability). This is logical since emulsifying properties of myofibrillar proteins increases as pH approaches neutrality (Ordóñez et al., 1998). Note that according to Eq. (3), as pH approaches neutrality, metmyoglobin tends to produce oxymyoglobin, retaining more water.

The analysis of the effect of CT on cooking exudations and color parameters suggest that increasing lean proportion (i.e., reducing the R_{FL}) would increase the protein content, which will in turn increase both the concentration of myofibrillar proteins and myoglobin. The increase of myofibrillar proteins (mainly myosin) would enhance fat globules stabilization, decreasing lightness and yellowness of the raw emulsion and reducing the exudation of fat during cooking, while the increase in myoglobin would promote the redness of the emulsion. Thus, a positive correlation of C_{LF} with L^* and b^* and a negative correlation between C_L and a^* should be expected, as it can be observed in Table 5. These results agreed with previous studies by Álvarez, Castillo, et al. (2007). These authors claimed that only two significant color parameters L^* and a^* showed potential for prediction of C_L in pork meat emulsions. Note that from our results, L^* and b^* appear to contain information related to fat exudation while a^* seems to carry information about myoglobin content and its water holding capacity as a function of pH.

3.3. The effect of chopping time on light backscatter measurements

The LSM presented in Table 4 show a significant ($P < 0.001$) increase of IT and decrease of light backscatter intensity (e.g., I_{Nmax}

and I_{Nmin}) with increasing CT. Fig. 4 shows the effect of CT on the light backscatter intensity spectral scan at different radial distances from the light emitting source. For the three radial distances studied (2, 2.5, and 3 mm), the light backscatter intensity parameters I_{Nmax1}, I_{Nmax2}, and I_{Nmax3} decreased by an average of 23%, 43%, and 46%, respectively, as CT increased from 2 to 8 min. It was also observed that those light backscatter intensity parameters decreased by an average of 14%, 25%, and 38%, respectively, as distance between fibers increased from 2 to 3 mm, regardless of the CT studied (2, 5, and 8 min). Thus the highest lost of intensity as a result of chopping takes place at λ_{max2}, and λ_{max3} (620 nm and 690 nm, respectively), while the high lost of intensity as a result of distance between fibers takes place at λ_{max3}. These results suggest the use of short distances between fibers and a local spectral scan around 690 nm (red region) to obtain the highest resolution in the light backscatter signals during the meat emulsions comminuted process. This finding will assist on the development of an optical sensor technology able to associate changes in light backscatter intensity during the chopping process with emulsion stability parameters.

Fig. 5 shows the effect of CT on the average of the maxima (I_{Nmax}) and minima (I_{Nmin}) light backscatter intensity values corresponding to the green–yellow (I_{Nmax1} and I_{Nmin1}), orange–red
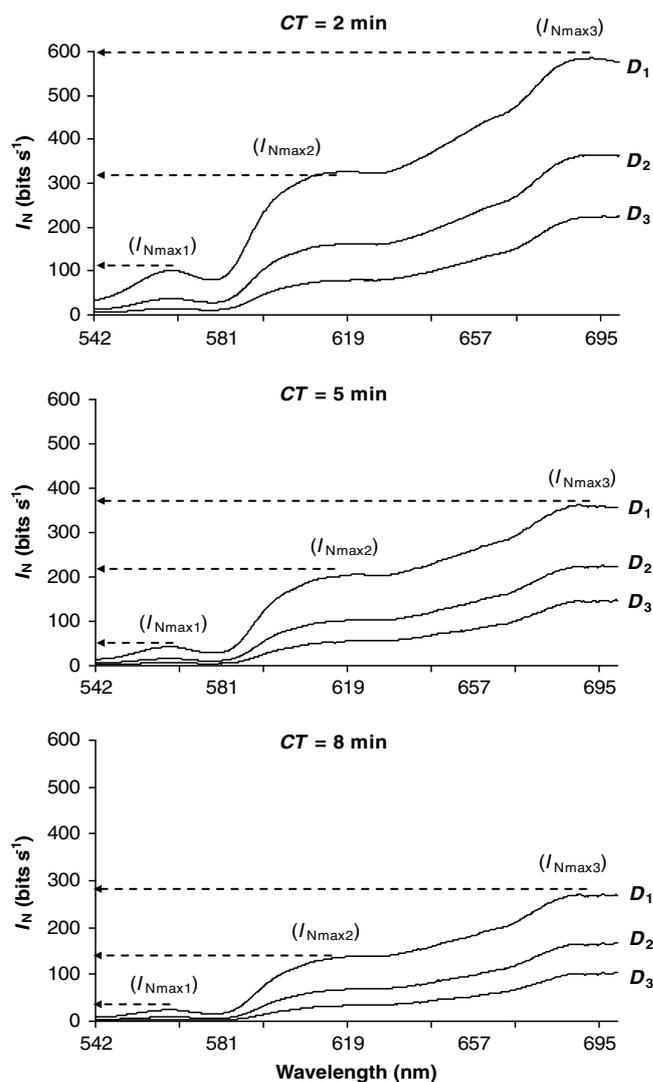

Fig. 4. Effect of chopping time (CT) on the light backscatter intensity at different radial distances from the light emitting source.
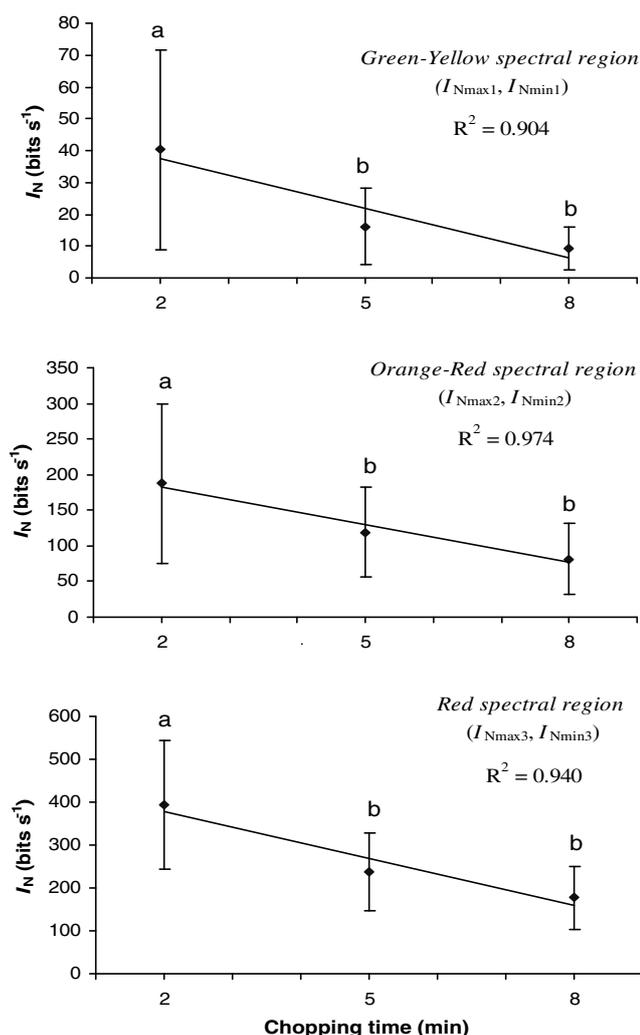
Fig. 5. Effect of chopping time on the average of local maximum and minimum light backscatter normalized intensity at three spectrum regions; green–yellow, orange–red; and red (●). The averages at different *CTs* (*N* = 27) are calculated using nine trials over a range of three R_{FL} levels and three distances (3 replications per treatment). Error bars corresponded to ±1 SD interval of the average value. Average with the same letters was not significantly different (*P* < 0.05).

(I_{Nmax2} and I_{Nmin2}) and red (I_{Nmax3} and I_{Nmin3}) spectral regions. It was observed that the average and standard deviation of light backscatter intensity in the three regions were significantly (*P* < 0.05) higher at *CT* = 2 min than at 5 or 8 min. The decrease of light backscatter intensity with chopping duration was observed to be non-linear, and the decrease was more evident in the green–yellow region. As it can be observed by the behavior of the standard deviations, light backscatter intensity measurements were less repeatable at the beginning of the chopping process (*CT* = 2 min) when the heterogeneity of the samples was market. However, light intensity measurements became smoother (repeatable) towards the end of the chopping (*CT* = 8 min) when the sample was more homogeneous. These results clearly show that as the meat sample becomes more homogeneous as a result of the chopping process (i.e., particle size decreases), it is more difficult for the visible light to pass through the sample. This is logical as light scattering intensity is not only proportional to particle concentration but also depends, among other properties, on the material of the particle (i.e., the complex index of refraction) and its size parameter ($\pi d/\lambda$, where *d* is the diameter of the particle) (Modest, 2003).

According to Álvarez, Payne, Castillo, and Xiong (2007), monitoring meat emulsification would require a sensor capable of providing a representative signal from the beginning of the process, when the sample is extremely heterogeneous, to the end of the process, when the sample is relatively homogeneous. It is reasonable to assume that a light backscatter signal obtained using multiple groups of emitting and detecting fibers spaced to collect an optical signal over a large sample area would compensate for the large heterogeneity of the matrix. Our results suggest that an on-line light backscatter sensor might be able to provide the useful information about the meat emulsification process. According to Barbut (1999), this optical information can be used to optimize the chopping process and prevent over-chopping (i.e. emulsion breakdown) and/or energy waste if chopping is continued unnecessarily for too long.

3.4. The effect of fat/lean ratio on color and meat emulsion quality metrics

Table 4 shows that LSM of fresh emulsion color parameters L^* and b^*, increase (*P* < 0.001) with increasing R_{FL}. The minimum redness values, a^*, were observed in emulsions having the highest R_{FL}, which was attributed to lesser levels of myoglobin content as introduced above. Other authors have reported similar findings on fresh beef frankfurters (Paneras, Bloukas, & Papadima, 1996; Boles et al., 1998). Further, R_{FL} also exerted a direct effect on cooking losses. As it can be observed in Table 4, meat emulsions having higher R_{FL} were also found to have larger C_L (*P* < 0.001). The significance of R_{FL} on meat emulsion stability was previously reported by Álvarez, Castillo, et al. (2007). According to these authors, proper protein coating of fat globules before cooking requires an adequate R_{FL} that ensures enough extraction of soluble proteins (i.e., myosin) from the cell structures during chopping. In agreement with Barbut (1998), emulsions with higher R_{FL} were more difficult to stabilize and had a significant (*P* < 0.001) increase of water (*r* = 0.75) and fat (*r* = 0.59) losses during the heat treatment. Allais, Christophe, Pierre, and Dufour (2004) were observed a similar effect of R_{FL} on meat emulsion C_L, although no significant differences were detected for color parameters.

3.5. The effect of fat/lean ratio on light backscatter measurements

It was found that light backscatter intensity at the local maxima and minima (I_{Nmax} and I_{Nmin}) significantly (*P* < 0.05) decreased when R_{FL} increased from 0.25 to 0.33, while the *IT* significantly (*P* < 0.05) increased (Table 4). The effect of R_{FL} on the remaining optically generated parameter was not conclusive. The effect of R_{FL} on the light backscatter intensity spectral scan at different radial distances from the emitting source (*D*) is shown in Fig. 6. As it can be observed, light penetration through the sample decreases with increasing R_{FL} levels. This is logical as light scattering intensity depends, among other properties, on particle concentration (Modest, 2003). It is also observed that light backscatter intensity tends to increase (although the increase was not significant – see Table 4) when R_{FL} increased from 0.075 to 0.25. Further increase of R_{FL} produced a decrease of intensity rather than an increase. The observed pattern is considered to be related to the aqueous nature of meat fat dispersion in the emulsion matrix. Note that the primary components of meat emulsions associated with their light scattering properties are fat globules and broken microstructural constituents of lean tissue such as rests of myofibrilar proteins, sarcoplasmic proteins, connective tissue, etc. (Michels, Foschum, & Kienle, 2008; Swatland, 2004; Xia, Weaver, Gerrard, & Yao, 2008). Thus, it is expectable that at low fat concentration, meat emulsion light backscatter intensity increases with fat concentration. However, as fat concentration increases, a point is
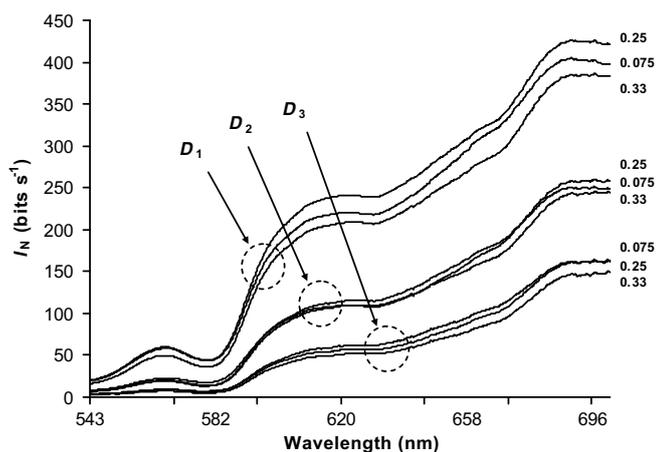
Fig. 6. Effect of fat/lean ratio on the light backscatter intensity at different radial distances (D) from the light emitting source.

reached when proportionality between concentration and intensity no longer holds. A very similar pattern was observed by Castillo et al. (2005). Working within a range of milk fat concentration in whey, these authors found that, once a certain concentration of fat was reached ($\sim$0.4%), sidescatter intensity measured at 425 nm saturated and declined even though the concentration increased. Payne, Zhou, Sullivan, and Nokes (1997), working with milk having different fat levels, also observed a decrease in light penetration distance with increasing milk fat level.

3.6. The effect of distance between optical fibers on light backscatter response

As it can be observed in Table 4, the LSM of the normalized intensity spectral scans (I_{Nmax} and I_{Nmin}) significantly ($P < 0.001$) and exponentially decays as the radial distance between the emitting and detecting fibers increases. This trend is also observed in Figs. 4 and 6. Subsequently, and irrespectively of the CT and R_{FL} considered, the intensity measured at all the local maxima and minima always decreased with increasing distance. Also, a significant increase of IT ($P < 0.001$) and Pk ($P < 0.05$) was noticed as radial distance from the light source increased, which translates

into gradual and noteworthy lost of response resolution. These results agree with previous studies carried out in skim milk by Crofcheck, Payne, Hicks, Mengüç, and Nokes (2000). These authors claimed that light scattering dominates in skim milk for transmission distances less than 5 mm and decreases exponentially as radial distance from the emitting site increased. On the other hand, the wavelength at the third light backscatter local maximum, λ_{max3}, was observed to shift significantly ($P < 0.001$) from 682 to 691 nm as D increased from 2 to 3 mm.

As it is shown on Table 6, radial distance does not only exert a distinct effect on fresh meat emulsion light intensity spectral scans but also impacts the correlation of optically generated parameters with CT and heat treated emulsion quality metrics. Since the behavior of local maximum intensities (I_{Nmax}) was found to be very similar to that for local minimum intensities (I_{Nmin}), in Table 6, only local maximum intensities (I_{Nmax}) were shown. It was observed that the Pearson correlation of IT and Pk with CT and all the metrics studied with the exception of pH (T, L^*, a^*, b^*, and C_{LF}) decreases with increasing D. The correlation of all these meat quality metrics with wavelength at the different light backscatter maxima/minima had varying trends as a function of D. For instance, while λ_{max3} had the higher correlations at 3 mm, λ_{min3} had the smaller correlations at 2.5 mm. Regarding to local maxima intensities, it was observed that I_{Nmax1} and I_{Nmax3} had slightly decreased correlations and significance levels with all the meat emulsion quality metrics as D increased, except for C_{LF}. I_{Nmax2} presented higher correlation and significance level with CT, T, L^*, b^*, and C_{LF}, at 3 mm and with pH and color coordinate a^* at 2 mm. The best correlations and significant levels detected in Pk and light backscatter intensity at 2 and 2.5 mm suggest the use of short distances between the detecting optical fibers and the light source to design an optical sensor technology able to monitor the meat emulsion process. According to previous studies by Payne et al. (1997), determining the appropriate spacing between fibers is one of the most important factors in the development of light backscatter sensor technologies. Our results indicate that meat emulsion stability could be determined by light backscatter measurements, if different distances between fibers are taken in account. According to our results, we propose the optical configuration showed in the Fig. 7. This configuration considers that a light backscatter signal obtained using multiple pairs of emitting and detecting fibers spaced to collect an optical signal over a large sample area would

Table 6
Pearson correlation of light backscatter parameters IT, Pk and local maxima of the red spectral region with color parameters and meat emulsion quality metrics as a function of the distances from the emitting light source[a]

$D = 0.2$	CT	pH	T	L^*	a^*	b^*	C_{LF}
IT	0.94***	0.41*	0.81***	0.79***	0.38*	0.65***	0.67***
Pk	0.81***	0.40*	0.76***	0.77***	ns	0.74***	0.69***
λ_{max3}	−0.70***	−0.57**	−0.48*	−0.43*	−0.52**	−0.42*	ns
I_{Nmax3}	−0.93***	−0.69***	−0.78***	−0.76***	−0.63***	−0.71***	−0.60**
$D = 0.25$							
IT	0.89***	ns	0.77***	0.75***	ns	0.58**	0.66***
Pk	0.63***	0.50**	0.40*	ns	0.57**	ns	ns
λ_{max3}	−0.63***	−0.60***	−0.45*	−0.43*	−0.59**	−0.49*	ns
I_{Nmax3}	−0.92***	−0.68***	−0.78***	−0.75***	−0.60***	−0.68***	−0.61***
$D = 0.33$							
IT	0.86***	ns	0.75***	0.67***	ns	0.49**	0.60***
Pk	0.56**	0.67***	ns	0.49**	0.50**	0.48*	0.42*
λ_{max3}	−0.83***	−0.75***	−0.61**	−0.57**	−0.72***	−0.62***	−0.47*
I_{Nmax3}	−0.91***	−0.61**	−0.72***	−0.71***	−0.57**	−0.66***	−0.60**

For the definition of dependent variables, see Section 2.
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
ns not significant.
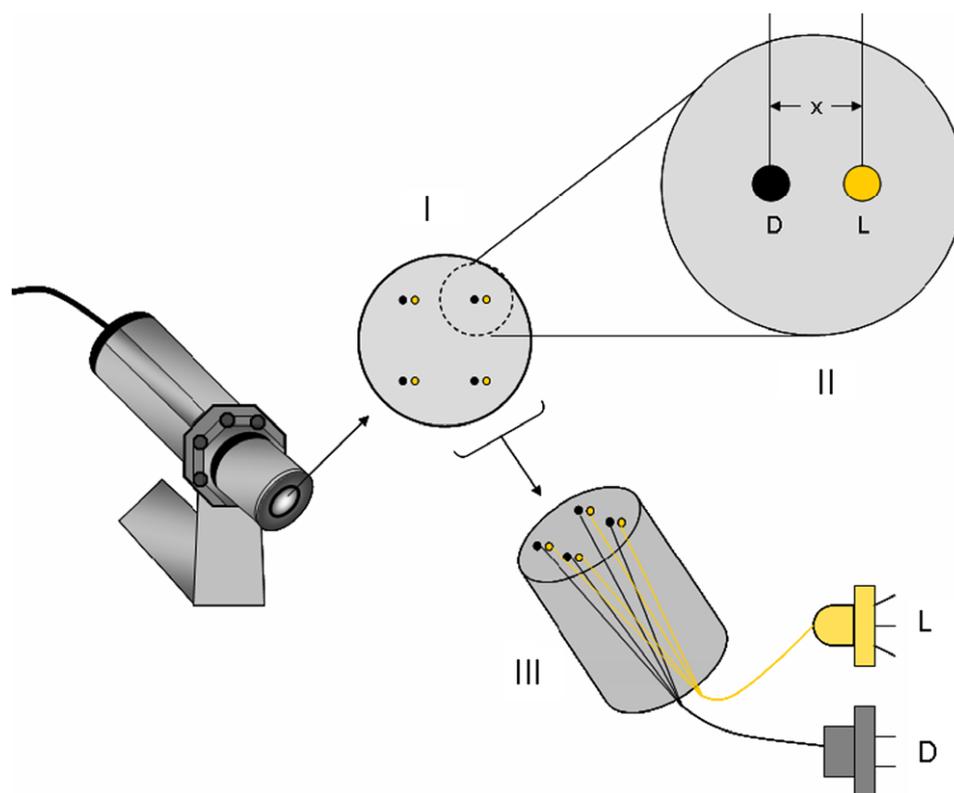[a] $N = 27$ for each distance studied.

Fig. 7. Configuration of the optical backscatter sensor for measuring meat emulsion. (I) cross-section of the sensor tip showing four detection units; (II) detail of a single detection unit showing the separation between emitting and detecting fibers; (III) side view of the sensor tip showing the confluence of the emitting and detecting fibers from each one of the four detection units into two single fibers toward the light source (*L*) and the detector (*D*), respectively.

compensate for the large heterogeneity of the matrix during chopping. Another uniqueness of this optical configuration is that the backscattered light received at the detector has been transmitted-through a specified path-length (*x* in Fig. 7) of the emulsion making it essentially a transmission mode sensor. The ability of this configuration to measure a property related to homogenization is considered far superior to the use of diffuse reflectance from the surface of the meat.

4. Conclusions

Chopping time and fat/lean ratio were found to exert a great impact on meat emulsion stability. Chopping time had an indirect effect on coking losses through changes of pH, temperature and particle size occurred in the matrix during the chopping process while the fat/lean ratio had a direct effect on fat losses during the emulsion cooking process. Light backscatter measurements can be used to monitor physical–chemical changes in comminuted meat products during the emulsification process. It was observed that light scatter intensity decreased logarithmically with increasing distance between the emitting and detecting optical fibers. Further, light propagation was found to decrease as chopping duration and fat-lean ratio increased. Fattier and over-chopped emulsions not only presented smaller light backscatter intensity, but also were more unstable and had more cooking losses during manufacturing. A consistent shift to longer wavelengths was observed at the local maximum (I_{Nmax3}, λ_{max3}) when the radial distance between the optical fibers increased. The existing correlation between light backscatter parameters generated during the comminuting process with color coordinates L^* and a^* and cooking losses strongly support the potential development of a new on-line light backscatter sensor technology to monitor the degree of emul-

sification and minimize cooking losses in finely comminuted mean products. However, further studies are required to conclude if the proposed light backscatter parameters contain enough information to accurately determine the end-point of chopping and control the cooking loss. The results obtained suggest that the optimum sensor configuration for an optical meat emulsion stability sensor would use multiple measurements groups (i.e., detecting fibers surrounding an emitting fiber) spaced over a relatively large area. It is also proposed that the radial distance between the emitting and the detecting fibers within a group to be preferably smaller than 2.5 mm. This configuration would allow integrating the optical signal providing a representative signal from the beginning of the chopping process, when the sample is extremely heterogeneous to the end of the process when the sample is relatively homogeneous.

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